

Large Space Telescope

Abstract: The Large Space Telescope, which is scheduled to be put into orbit above the Earth's atmosphere by NASA in the early 1980s, is a large, multipurpose optical instrument that is being designed to provide an increase in observational capability of nearly 100× with respect to brightness, 10× in resolving power, and a substantial bandwidth improvement over ground-based facilities. This paper describes, from a functional performance viewpoint, the LST system and, in greater detail, the on-board Data Management and Pointing Control Systems.

Introduction

The concept of a powerful telescope operating in Earth orbit developed gradually during the last few decades. More than fifty years ago it was pointed out by astronomers that an optical telescope in orbit above the Earth's atmosphere would have three advantages over ground-based instruments. First, images produced by such an instrument in space would be free of the distortion produced by variable refraction in the Earth's atmosphere; more simply, stellar images would be steady and ideally sharp pictures could be obtained subject only to the limitation imposed by the diffraction of light waves. Second, electromagnetic radiation of most wavelengths could reach an orbiting telescope from a distant star without the nearly complete atmospheric absorption that prevents gamma rays, x rays, ultraviolet light, and some infrared wavelengths from reaching the Earth's surface. Third, a telescope in a satellite would be virtually weightless, thus permitting great optical-figure stability and mechanical alignment free from the perturbations produced by gravity-induced flexure.

Beginning in about 1968, preliminary design concepts were formulated for a large orbital telescope. These efforts have evolved into the NASA Large Space Telescope (LST) project.

The LST will be a 2.4-meter-aperture Cassegrainian system [1] of Ritchey-Chretien design. The system focal ratio of $f/24$ provides a 300-mm curved field of view, over which the image is nearly diffraction-limited. The bandwidth or wavelength response of the optics is determined almost entirely by the coatings used on the mirror surfaces. These mirrors will concentrate photons effectively throughout the wavelength range from 91 nm (910 Å) to 1 mm.

The attitude or Pointing Control System planned for the LST can point the telescope in a given direction with an accuracy of 0.01 arc-second and can remain stable

within ± 0.007 arc-second on a single target for extended periods of time (0.007 arc-second is, for example, the angle subtended by a U.S. 25¢ coin at a distance of 400 miles).

The largest Earth-based optical telescope in operation today is the 200-inch Hale telescope at Palomar Mountain, California. It can "see" an estimated 10^9 to 10^{10} light years into space. The Hale telescope, like all Earth-bound viewing devices, has distorted vision because the Earth's atmosphere blurs the view and "smears" the light. Under good conditions, point sources of light appear as approximately one-arc-second images. In contrast, the LST is expected to be as much as 10 times better; i.e., point sources of light will appear as 0.13-arc-second images. This capability will permit resolution (according to the Rayleigh criterion [2]) of objects separated by only 0.06 arc-second.

With the Large Space Telescope, scientists will be able to examine celestial objects such as quasars, pulsars, galaxies, gaseous nebulae, and Cepheid variable stars that lie far beyond the viewing capability of the largest present Earthbound telescopes, and to study nearer objects that lie within the solar system. In addition, the LST will be used to gain a better understanding of the energy processes in celestial bodies.

Some of the specific research projects planned for the orbiting telescope include the following.

- *Determination of stellar mass*

Our knowledge of the mass of stars is derived from the orbits of binary (double-star) systems. The mass-luminosity relation [3] is defined by fewer than 100 stars whose masses are known to an accuracy of only about 12 percent. Since the relative error in mass is three times the relative error in parallax, to halve the uncertainty in mass the latter must be known with an accu-

Table 1 Surface-feature resolution capability of the LST (D is the object diameter).

<i>Celestial object</i>	<i>h (km)</i>	<i>D/h</i>
Eros (asteroid)	2	8
Venus	8	1500
Mars	11	610
Mercury	18	260
Ceres (asteroid)	27	26
Jupiter	120	1180
Saturn	250	480
Uranus	550	90
Neptune	870	54
Pluto	1100	5

racy of two percent. Similarly, velocity changes in binary orbits must be measured with two-percent accuracy if velocity is to be used for mass determination instead of parallax. The LST will provide a capability for obtaining those levels of accuracy.

- *Expansion of the universe*

Although the basic constants of physics are now known to many significant figures, fundamental values corresponding to the large-scale structure and dynamics of the universe are uncertain, even in the first significant figure. One of the most important of these cosmological parameters is the Hubble constant H_0 , which represents the apparent rate of expansion of the universe as determined by the redshift of galaxies. During the last several decades, both major and minor corrections have been made in the value assigned to H_0 ; the net effect has been a reduction in magnitude by a factor of ten. Although the current value of H_0^{-1} , approximately 1.8×10^{10} years, is close to the age of the oldest known objects in the universe, the uncertainty in H_0 remains significant.

Some cosmological models predict a departure from linearity in the velocity-distance relation apart from the effect of acceleration or deceleration in the expansion of the universe. Within the distance limit of several billion parsecs [4] set by ground-based observations of giant galaxies, the fundamental parameter q_0 , which measures this nonlinearity, cannot be determined within ten percent accuracy. However, with a large, high resolution instrument in space, such as the LST, the velocity-distance relation for galaxies can be extended to more distant objects and made more precise for closer objects, thus yielding improved values for both H_0 and q_0 .

- *Solar system*

Certain aspects of the study of planetary atmospheres and surfaces are particularly suited to the capabilities of

the LST. For example, for Venus and Mars, the nearest planets to Earth and the objects of extensive investigation, scientists still need high resolution observations extending over planetary seasons and the solar cycle to complement the information gained by flybys, orbiters, and surface-landing vehicles. Also, with a resolving power of 0.06 arc-second, there can be an order of magnitude reduction in the size of the smallest topological feature that can be resolved on a planet's surface. The size h of the smallest detail distinguishable by the LST on the surfaces of various bodies at their closest approaches to Earth is given in Table 1.

The Large Space Telescope is scheduled to be put into orbit in the early 1980s. The spacecraft containing the telescope and associated instruments and support equipment will be carried into Earth orbit by the Space Shuttle now being developed by NASA. The unmanned LST will orbit the Earth at an altitude of approximately 500 km (270 nautical miles) and an inclination of 28.8 degrees. It will have a 10- to 15-year operational lifetime and will be returned periodically to Earth by the Space Shuttle for maintenance, refurbishment, and upgrading. The Shuttle will not only launch the LST into orbit and retrieve it, but it will also serve as a base from which astronauts can make repairs and possibly replace instrument packages.

The LST program is currently in a preliminary design phase [5]. The final design will be selected in March 1976. IBM is contributing to this program as a subcontractor to the Martin Marietta Corporation and has the role of designing the Data Management and Pointing Control Systems [6].

LST system

Figure 1 shows schematically the general features of the LST system. The spacecraft consists of three major elements: the Optical Telescope Assembly (OTA); the Science Instruments (SI); and a Support Systems Module (SSM). The spacecraft is linked to the LST ground facility by two separate communication systems, the Tracking and Data Relay Satellite System (TDRSS) and the Spacecraft Tracking and Data Network (STDN). Commands to the spacecraft and scientific and engineering data from the spacecraft are transmitted via these systems. The LST will function effectively with either or both communication systems. The STDN is now used for tracking and communicating with satellites. The TDRSS is a geosynchronous communication satellite system currently in the planning phase.

The existing NASA communication network (NASCOM) can be used to route data from TDRSS and STDN ground stations to the LST ground facility. Functionally, the LST ground facility will perform mis-

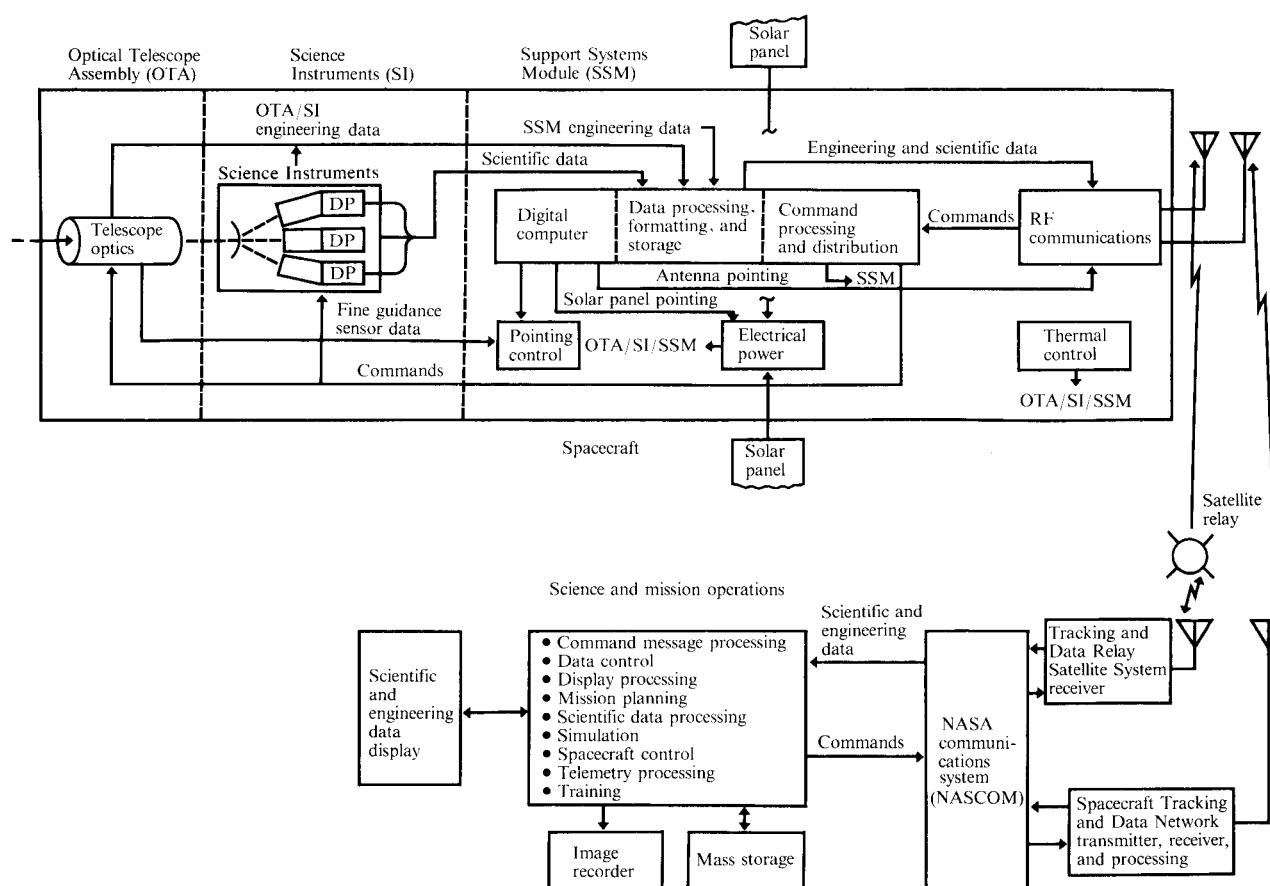


Figure 1 Schematic diagram of the Large Space Telescope system.

sion and observation planning; prepare spacecraft commands and data for display to spacecraft controllers and resident astronomers controlling the spacecraft instruments; and provide capability for training, for controlling the spacecraft, and for revising and updating software and hardware. A scientific data processing capability is planned for use by guest observers. Remote terminals may be provided to enter observation requests to the LST facility and to receive a limited amount of data from the LST ground facility.

Communication antennas are gimbaled so that they may be pointed, under computer control, to the TDRSS antenna regardless of telescope attitude. The solar arrays are oriented toward the sun, also under computer control, to keep a uniform flow of power into the spacecraft when the spacecraft is in sunlight. Batteries charged by power derived from the solar panels during the sunlit portion of the orbit provide power during orbital night.

Baffles in the main telescope housing are required to reduce stray light to an acceptable level. Considerable care must be exercised in the design of the structure to assure that thermal stresses do not distort the optical path. The main telescope structure may be made of graphite epoxy, a low coefficient-of-thermal-expansion material. The design objective is to keep wavefront errors less than $1/20$ of a wavelength at 632.8 nm ($6328 \text{ \AA}$). The principal wavefront error contributor is the mirror figure. Insulation blankets and heaters are provided to maintain temperatures in critical areas within given bounds, thereby reducing thermal effects on the primary mirror.

The Science Instrument bay will initially contain four basic instrument modules, with the instruments to be selected from the set described in Table 2. Virtually all of the scientific data transmitted to the LST ground facility from the spacecraft will emanate from imaging devices and will be in the form of digitized image data.

Table 2 Proposed instrument complement for the Large Space Telescope.

<i>Instrument</i>	<i>Characteristics</i>	<i>Uses</i>
Field camera	$f/24$ with SECO ^a detector 2000 × 2000 pixels Photometric accuracy of 3 percent Imaging to $m_v = 29$ Relatively low resolution	Extragalactic research: imagery and photometry of distant galaxies Wide-field surveys
Planetary camera	CCD ^b detector at $f/48$ 400 × 400 pixels Photometric accuracy of 0.5 percent Sensitivity to 200 nm and 1.1 μm Relatively high resolution	Planetary and bright-object work Nuclei of nearby galaxies Emission nebulae
	CCD detector at $f/96$ Polarimetry, photometry, photon counting Very high resolution	Photometry of very faint objects Measurement of galactic-core radii
High speed, point/area photometer	Aperture $\approx$ image size, ICCD ^c detector Range 115 to 650 nm Measures non-periodic time variations 1 ms to 1 s; periodic, to 100 μs	Magnitude and color of planets, stars, galaxies, and extended objects
Faint-object spectrograph	Acquisition: slit-jaw camera, ICCD detector Selectable resolution 10^2 to 10^4 Imaging m_v limit 22.5 to 25.5 Spectrograph-detector ranges: 90 to 190 nm; 180 to 400 nm; and 380 to 800 nm	Low dispersion work on stellar and quasi-stellar objects Ultraviolet spectra of x-ray sources and distant galaxies Polarization studies Study of satellites, comets, planets, planetary nebulae, and the interstellar medium
High resolution spectrograph	Acquisition: post-slit viewing Resolution about 10^5 , SECO detector Imaging m_v limit about 17.5 Spectrograph-detector ranges: 115 to 170 nm (far ultra-violet) and 170 to 410 nm (Echelle)	Stellar absorption and emission lines Sharp-lined early stars Interstellar absorption Study of comets, planets, nebulae, and extra-galactic objects
Infrared photometer	Aperture $\approx$ image size Resolution of 1000 levels Filter photometry from 2 μm to 1 mm Detector cooling to 2 K Chopper required	Infrared stars Galactic center Extra-galactic nuclei H II regions Planetary studies
Astrometer	Principal element is either the fine guidance sensor or a modified multiplex area scanner	Measure parallax and proper motion, angular diameters, and star masses (for spectroscopic binaries)

^aSecondary electron conduction orthicon^bCharge-coupled device^cIntensified charge-coupled device

The Support System Module, located at the rear of the LST spacecraft, contains equipment for electrical power storage, regulation, and control; thermal control; communications; pointing control; data processing; communication antennas; and solar panels.

Data Management System

Figure 2 is the block diagram of a proposed LST on-board (spacecraft) Data Management System. For simplicity, equipment redundancy is shown only as the number of redundant components and is given in parentheses within each block in the diagram. Redundancy is required to meet Data Management System reliability

goals and the no-single-point failure requirement for the LST.

The computer system shown in Fig. 2 is a configuration consisting of a Five-Fault-Tolerant Memory, two Central Processing Units (CPUs), two Input/Output Processors (IOPs), a Fault Detection Unit (FDU), and an Auxiliary Memory and Memory Load Unit (AMMLU). The CPUs and IOPs operate in a one-on, one-off mode with both CPUs interfacing with the single Five-Fault-Tolerant Memory. For reliability purposes, three power supplies are cross-strapped and supply power to all units. All external systems interface with

DCS: Digital Command System
DMA: Direct Memory Access
I/F: Interface
TM: Telemetry

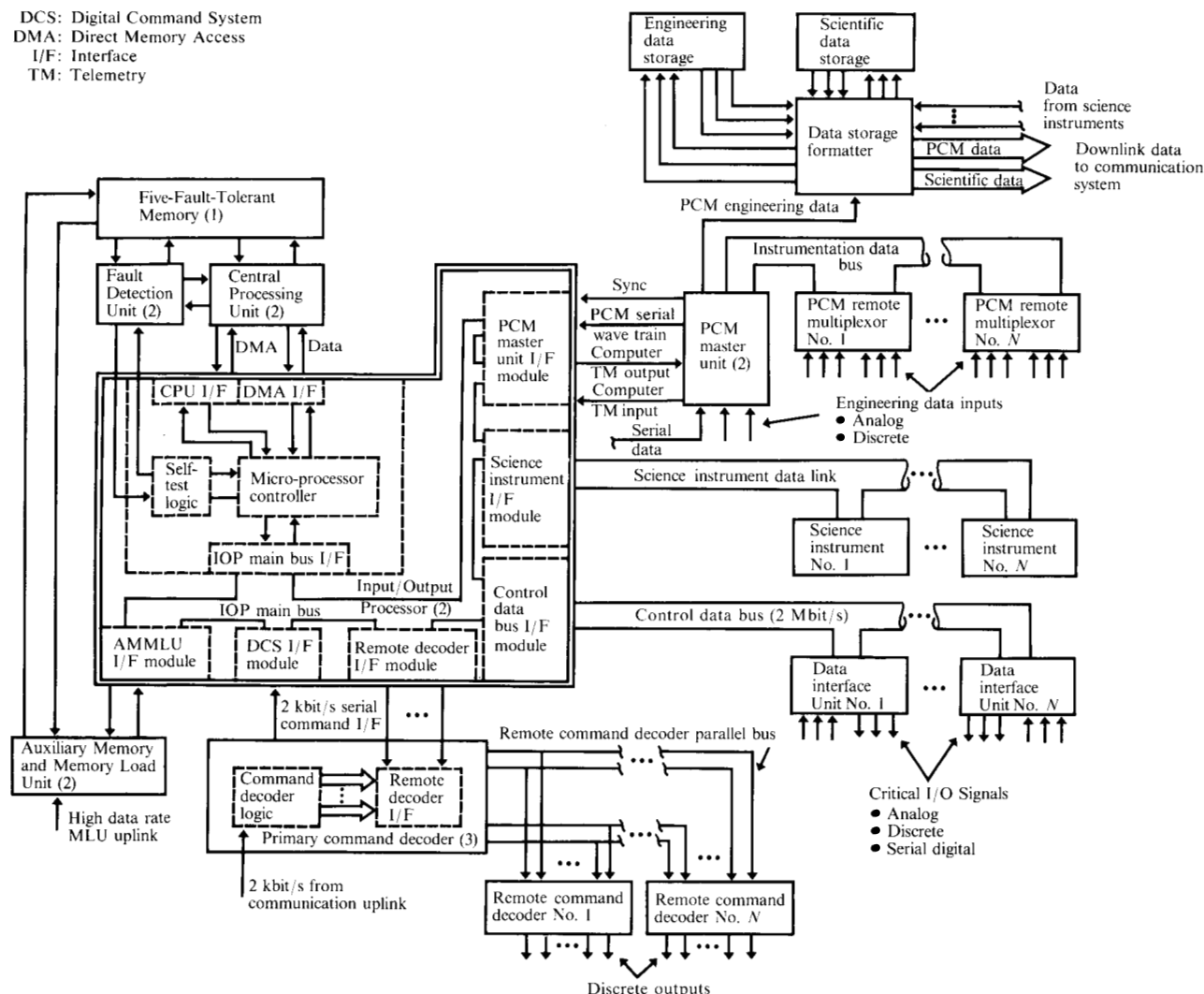


Figure 2 Proposed LST spacecraft Data Management System.

the computer system through special IOP interface modules. The FDU controls the computer system configuration based on detected faults. The AMMLU provides auxiliary storage for commands and special purpose subroutines. Memory load capability exists either from auxiliary storage or via two separate paths, MLU uplink and communication uplink.

All flight-critical input data are acquired through the control data bus via Data Interface Units. Flight-critical signals are considered to be those signals required for fine pointing control, solar panel pointing, and high-gain antenna pointing.

All discrete output signals are provided to spacecraft subsystems through the Remote Command Decoders (RCDs). This configuration allows priority ground command of any discrete output with or without computer

intervention; the computer may issue outputs based on an uplinked stored sequence or as part of routine computer operation.

Uplinked commands are received from the communication system by the Primary Command Decoders (PCDs); if it is a direct discrete output command, it is issued directly to the RCD; if it is a stored or computer-addressed command, it is sent to the computer for later issuance or processing. The PCD also handles contention problems that result from computer-originated and direct commands being issued to the RCDs over the same path (the RCD parallel bus).

Non-flight-critical analog, discrete, and serial digital input measurements are acquired through a conventional pulse code modulation (PCM) telemetry system consisting of a master unit and remote multiplexors. This

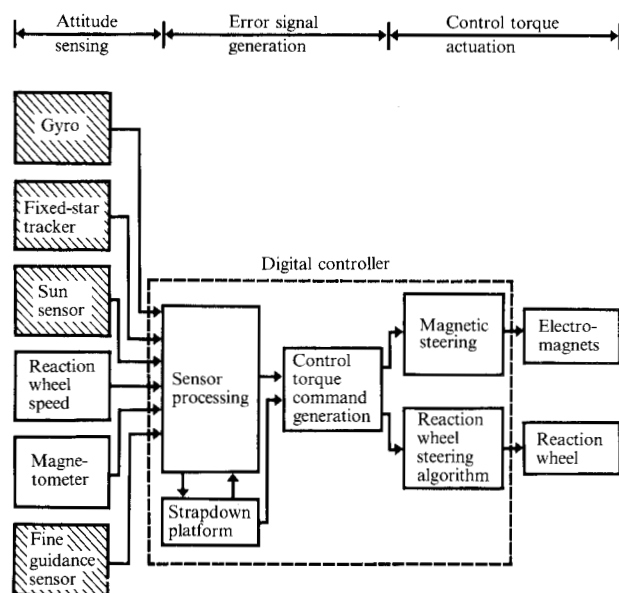


Figure 3 Functional block diagram of the LST Pointing Control System proposed design (attitude sensors appear as cross-hatched boxes).

system provides engineering data for downlinking and/or on-board storage. All PCM data are available to the computer system through a special IOP interface.

The Data Storage and Formatter Assembly routes all PCM engineering and scientific instrument data to either on-board storage or the appropriate downlink transmitter. Computer access to scientific data has been provided in this design for target acquisition verification purposes.

The ground portion of the LST Data Management System can be thought of as having three distinct functions: 1) processing of scientific data, including information on the status of instruments important to the interpretation of scientific data; 2) processing of data associated with the status and control of the spacecraft and its subsystems; and 3) data processing associated with mission and observation planning and command preparation.

Scientific data, mostly digitized image data, will be corrected [7] for geometric distortion introduced by the telescope optics and by radiometric variations in the image devices. Other corrections based on orbital position and velocity, background radiation, optical system focus, spacecraft attitude, instrument parameters, and guidance sensor errors will be made before the data in digitized image format are given to the user. The user (guest observer) will also be given sufficient information so that he can analyze the raw, uncorrected data if he chooses. Hardcopy photographs made from the cor-

rected data will be provided with each data tape, along with an historical record of the processing performed. Typically, data obtained from the LST will be stored for future reference, as are photographic astronomy data obtained at ground-based observatories.

It is expected that uncorrected image data will be presented to a resident astronomer during the actual observation so that he can verify that the telescope is pointing at the object he wants. If it is not, he can re-direct the telescope to the desired object. Since many of the objects observed by the LST will be very faint, it will take time to build up an image. With a limited field of view, some searching may be required to locate the desired object.

Engineering data processing includes comparisons of spacecraft measurements with standard values, thus indicating the "health" of LST subsystems; conversion of raw telemetry data to engineering units; and preparation of data for display to monitoring personnel. The design objective is to automate as much as possible the monitoring of engineering data and, as a direct consequence, reduce the number of personnel dedicated to spacecraft operations.

Pointing Control System (PCS)

The LST line-of-sight pointing accuracy requirement of 0.01 arc-second, with a long term pointing stability of 0.007 arc-second, is by far the most demanding pointing requirement in the history of spacecraft design. Because of the LST's stringent pointing requirement, the control system must account for dynamic effects previously neglected in attitude control system designs. For example, sensor noise, image motion induced by rotor vibrations in control torque actuators, friction characteristics of moving elements, and effects of digital computer word length (quantization) become significant factors in the LST Pointing Control System design.

The Pointing Control System is partitioned into three major functions: attitude sensing, control signal generation, and control torque actuation. A functional block diagram of the PCS design is shown in Fig. 3.

The attitude sensing function is accomplished with inertial rate-gyros, fixed-star trackers, sun sensors, and a fine guidance sensor. Integrating rate-gyros sense vehicle angular rate through the torque required to suppress precession of the rate-gyro rotor. Output signal pulses from each rate gyro are proportional to the instantaneous vehicle angular rate. These pulses are used to obtain either an average angular rate over a given time increment or an angular displacement.

Three Fixed-head Star Trackers (FST), each having an $8^\circ \times 8^\circ$ field of view, provide a celestial reference for the LST. Outputs representing star presence, star magnitude, and star position are provided by each FST to

the digital computer which, in turn, uses these quantities to revise the attitude reference computer from the analytic platform reference equations.

Two sun sensors provide the LST with a reference attitude relative to the sun line. Each sun sensor has a 2π -steradian field of view with a ± 0.1745 -radian ($\pm 10^\circ$) linear operating range. The sun sensor provides the means to recover attitude orientation from an arbitrary attitude.

The fine guidance sensor is located in the focal plane of the telescope and provides a three-axis attitude error signal referenced to pre-selected guide stars or reference stars located in the proximity of the desired target object. Guide stars are used to align the LST optical axis on the desired target (as opposed to direct feedback from the target) because of the extremely faint targets the LST is designed to view. The fine guidance sensor has coarse and fine operational modes with fields of view of 30 arc-seconds and 1 arc-second, respectively. Automatic transition between the two operational modes is provided.

Observations on solar system objects cause a more difficult pointing control problem than those of the relatively fixed, more distant stars because the telescope's optical axis must be moved precisely to follow the motion of the solar system objects. This is accomplished by providing the fine guidance sensor with a pre-computed sequence of guide-star coordinates that, in effect, describes the motion of the object to be tracked with respect to the guide stars. There is a forced movement of the guide-star image across the sensor reticle and the resulting error signals derived from the fine guidance sensor are used by the on-board computer to drive the telescope's optical axis along the path followed by the object being tracked.

A computed set of inertial platform gimbal angles (strapdown) is used in conjunction with attitude commands to generate attitude error signals. This function is performed analytically using sensed inertial angular rates. Because of platform drift resulting from sensor inaccuracies and the precision limitations inherent in digital calculations, the strapdown platform reference must be updated either periodically or continuously by information from other attitude sensors such as the star trackers.

A vehicle control law determines the required control torque commands to effect the desired vehicle attitude. Control torque commands are formed in the digital computer by a linear combination of the vehicle attitude error, the vehicle angular rate, and the integral of the attitude error. The gains associated with each of these parameters are variable and dependent upon the stability and performance characteristics desired for the LST in specific modes of operation.

Torques to control the LST are provided by reaction wheels and magnetic torquers, which manage the momentum state of the reaction wheels and are also used in an emergency backup mode. The reaction wheels provide spacecraft attitude control through torques based on the desired vehicle state and stability characteristics. Torque is generated by changing reaction wheel speed.

The Pointing Control System must counteract disturbing torques that act in only one direction for extended periods (gravity gradient torques). In time, reaction wheels would eventually reach their speed limits (saturate) and could no longer provide torque in that direction. The momentum management system provides means for producing torques that prevent reaction wheels from reaching their speed limits. For the LST vehicle, the momentum management system cannot constrain the attitude orientation of the vehicle because of long-duration-observation pointing requirements. A magnetic torque system, consisting of an array of four electromagnets, supplies the energy to create the desaturation torques for the LST momentum management system. Currents through the electromagnets generate a magnetic field which interacts with the Earth's magnetic field to produce a torque on the LST spacecraft. The momentum management function generates current commands to the electromagnets based upon a specified momentum management performance criterion. A magnetometer provides the computer with information on the strength and direction of the Earth's magnetic field.

Functionally, the magnetic torque system is analogous to the reaction wheel control system in that a torque command is translated into currents for the electromagnets. The magnetic torque system control law forms a torque command vector based on the difference between the desired and the measured momentum states of the reaction wheels.

Extensive simulation studies and laboratory work with actual components indicate that PCS design objectives can be met. The most critical component is the fine guidance sensor. Two proposed sensor designs are being developed independently to assure a successful Pointing Control System design.

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References and notes

1. A Cassegrainian telescope is a reflecting telescope in which a secondary convex mirror reflects the light from the collecting mirror back through a hole in the center of the collecting mirror.

2. Two overlapping diffraction patterns (images of point objects) may be resolved when the principal maximum of one pattern falls on the first minimum of the other.
3. See, for example, L. Motz, *Astrophysics and Stellar Structure*, Ginn and Company, Waltham, Massachusetts, 1970, Sections 1.16 and 14.2.
4. At a reference point at a distance of one parsec, the mean distance from the Earth to the sun (one astronomical unit) subtends an angle of one second; 1 parsec $\approx 3.1 \times 10^{16}$ m.
5. "Requirements and Guidelines Document for LST Study," NASA Marshall Space Flight Center, Alabama, December 31, 1974; revised June 25, 1975.
6. Contract GC5-0903000, Martin Marietta Corporation and International Business Machines Corporation, Federal Systems Division, January 2, 1975.
7. See, for example, the discussions by R. Bernstein, "Digital Image Processing of Earth Observation Sensor Data," *IBM J. Res. Develop.* **20**, 40 (1976, this issue) and R. H. Kidd and R. H. Wolfe, "Performance Modeling of Earth Resources Remote Sensors," *IBM J. Res. Develop.* **20**, 29 (1976, this issue).

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